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John Borden Bierman

AN INVESTIGATION OF FLOODING

VELOCITIES IN SMALL DIAMETER

PACKED COLUMNS

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A THESIS

Presented to

the Faculty of the Graduate Division

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In Partial Fulfillment

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John Borden Bierman

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AN INVESTIGATION OF FLOODING

VELOCITIES IN SMALL DIAMETER

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NOMENCLATURE

F is fraction of free volume in packed column, cu.ft./(cu.ft. column volume)

g is acceleration of gravity, ft./sec.^{2}

G is superficial mass velocity of gas (based on empty column), lb./(sec.)(sq.ft. cross-sectional area)

L is superficial mass velocity of liquid (based on empty column), (lb./(sec.)(sq.ft. cross-sectional area)

S is surface area of packing, sq.ft./(cu.ft. column volume)

U_o is superficial gas velocity (based on empty column), ft./sec.

ρ_G is density of gas, lb./cu.ft.

ρ_L is density of liquid, lb./cu.ft.

μ is viscosity of liquid, centipoises

CHAPTER I

INTRODUCTION

Packed columns are widely employed in various processes of the chemical and petroleum industries for providing intimate contact between a liquid and a gas phase or between two liquid phases. The major use is in diffusional operations which include absorption, stripping, scrubbing, distillation, and extraction. Most of the packed columns in service at the present time are employed to contact liquid and gas phases.

A packed column is essentially a vertical shell built upon an adequate foundation and filled with a loose porous bed of packing. A distributor is usually located at the top of the packing to properly distribute the liquid. Sometimes additional distributors are placed within the packed section for tall columns. The liquid flows down through the packing by gravity and is removed from the bottom of the column. The gas is admitted at the bottom of the packing and flows upward through the packing countercurrent to the liquid. Provision is made for the removal of the gas from the top of the column. The packing is supported by a packing support plate. Packed columns are rather simply constructed and have no moving parts. Packing may be made from a variety of materials to permit use under severe conditions such as in processes involving corrosive liquids or gases.

For a given through-put of liquid there is a maximum gas flow which will allow countercurrent contact without causing the liquid to fill the column and be carried out of the top. Also, for each gas flow there is a maximum liquid flow above which the liquid will not flow uniformly down the column.

The flooding point has been defined by White (1) as that condition of operation such that the slope of a plot of the logarithm of the pressure drop across the column versus the logarithm of the gas velocity, for a given liquid rate, changes abruptly from approximately two to a value approaching infinity. He described the mechanism of flooding in columns packed with Raschig rings using a system consisting of water and air. As the air velocity was increased for a fixed liquid flow rate, the liquid seemed to build up in the column, and for further increases in air velocity the amount of liquid hold-up increased and bubbling increased in violence until water was mechanically carried out of the top of the column by the air. This point was termed the visual flooding point. As the air velocity is increased the liquid hold-up increases, the area available for gas flow decreases, and the pressure drop across the column increases.

During operation at and above flow rates which cause flooding the efficiency of mass transfer is reduced and the cost of pumping is greatly increased due to relatively high pressure drop across the packed column. In general practice the flooding condition is avoided by operation at flow rates somewhat below those which cause flooding.

White also defines a loading point, which precedes flooding, as the gas velocity at which, for a given liquid rate, the slope of a curve of the logarithm of the gas velocity versus the logarithm of the pressure drop across the column first deviates from approximately two.

In the design of packed columns a knowledge of flooding velocities is necessary to determine the limiting gas and liquid rates. The optimum operating condition should be determined by an economic balance.

Although packed columns have been widely used for many years, adequate methods for predicting the limiting flow rates in packed columns under all conditions are still not available. A considerable amount of work has been done on this subject in recent years and several correlations of flooding velocities have been developed. The correlation of Sherwood, Shipley, and Holloway (2) is perhaps the most generally used.

Baker, Chilton, and Vernon (3) studied the distribution of liquid flowing in packed towers of various sizes, and for a variety of packing materials, with and without counter-current flow of gas. The system used was water and air. They concluded that there was a critical ratio of diameter of column to size of packing particle which controls the tendency for the liquid to concentrate near the column wall. At ratios greater than eight to one the liquid distribution remained uniform down the column while at lower ratios there was a marked tendency for the liquid to concentrate toward the column wall. However, for sufficiently large packed columns in which initial uniform distribution has been attained, the liquid distribution will remain uniform to a reasonable depth of packing.

Sherwood, Shipley, and Holloway (2) investigated flooding velocities in a two inch diameter column packed to a height of approximately four feet with one-half inch Raschig rings. They studied the effects of varying liquid and gas densities, liquid viscosities, and surface tension on flooding velocities. Flooding points were determined visually. The data obtained was correlated on a single curve by plotting logarithm $\frac{V_o^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$ versus logarithm $\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}$, where:

F is fraction of free volume in packed column, cu.ft./(cu. ft. column volume)

g is acceleration of gravity, ft./sec.^{2}

G is superficial mass velocity of gas (based on empty column), lb./(sec.) (sq. ft. cross-sectional area)

L is superficial mass velocity of liquid (based on empty column), lb./(sec.) (sq. ft. cross-sectional area)

S is surface area of packing, sq. ft./(cu. ft. column volume)

U_o is superficial gas velocity (based on empty column), ft./sec.

ρ_G is density of gas, lb./cu. ft.

ρ_L is density of liquid, lb./cu. ft.

μ is viscosity of liquid, centipoises

Using flooding velocity data for larger diameter packed columns taken from the literature, Sherwood et al. found that the flooding points were higher than the data taken in the two inch column. Their generalized correlation curve is based on data taken from the literature for dumped Raschig rings. Data for other miscellaneous dumped packing material was in good agreement with the generalized curve, while the flooding curve for stacked rings is considerably above that for dumped rings. Liquid surface tension was found to have a negligible effect on flooding velocities over the range reported.

Elgin and Weiss (4) studied the performance of a three inch diameter glass column successively filled with four different packing materials using a system of air and water. Reasonable agreement with the generalized correlation of Sherwood *et al.* was obtained. By plotting the square root of the superficial gas velocity versus the square root of the superficial liquid velocity on rectangular coordinates, a straight line was obtained for any one packing.

Empirical equations are presented by Sarchet (5) for use in predicting flooding velocities of rings and broken solids. Flooding velocity data were obtained using a column eight and five-eighths inches in diameter packed successively with one inch and one-half inch clay Raschig rings and special one inch carbon rings, having ribs on the outside and inside, packed to a height of two feet.

Flooding velocities were measured by Schoenborn and Dougherty (6) for five commercial packing materials using a system of air and water and two oils covering a range of kinematic viscosities of from one to thirty-eight centistokes. An eight and five-eighths inch diameter glass column packed to a height of two feet was employed in their work. The visual flood point was not found to coincide with that determined by a plot of pressure drop versus gas rate as described by White (1). The data thus obtained were correlated by plotting both logarithm $\frac{G}{\phi}\nu^{n}$ and logarithm $\Delta P_F \nu^{m}$, respectively, versus $\frac{L\phi}{G}$, where:

G is air mass velocity, lb./(hr.)(sq.ft.)

L is liquid mass velocity, lb./(hr.)(sq.ft.)

ΔP_F is pressure drop at flooding, in. of water/ft. of packing

ν is liquid kinematic viscosity, centistokes

ϕ is a factor correcting for gas density

n and m are exponents varying from 0.12 to 0.33 depending on the type of packing.

Also, using an eight and five-eights inch diameter column, Bain and Hougen (7) investigated flooding velocities for five different packing materials using a system of three oils with different viscosities and three gases representing a wide range of densities. An equation was developed based on the correlation of Sherwood et al. which was found to fit the experimental data with an average deviation of plus or minus six per cent.

Lobo, Friend, Hashmall, and Zenz (8) experimentally determined the characteristics of some of the more commonly used packing materials. From these data, they concluded that the major discrepancies in the flooding data reported in the literature were due to incorrect packing characteristics rather than to fundamental differences in experimental techniques. All available flooding data was recalculated using their empirically averaged values of the term S/F^3. By plotting these data it was found that the correlation of Sherwood et al. was improved from a maximum deviation of two hundred and fifty per cent to one of one hundred and twenty per cent.

Zenz (9) and Elgin and Weiss (4) are in agreement that a plot of the logarithm of the pressure drop versus the logarithm of the gas velocity is a smooth curve and has no breaks as described by White (1).

Lerner and Grove (10) presented a new theory of the mechanism of loading and flooding in packed columns which characterizes loading and flooding as being caused by wave formation in the liquid.

Newton, Mason, Metcalfe, and Summers (11) have obtained flooding data in a four inch diameter column packed with one-half inch Berl saddles to a height of seven feet using a system of air and various concentrations of aqueous Sterox SK solutions. The effect of surface tension was studied over a range of from thirty two to seventy two dynes per centimeter. These data were correlated well by introducing the cube of the ratio $\frac{\sigma_W}{\sigma}$ as a factor into the abscissa of a Sherwood type plot, where σ_W is the surface tension of the water, dynes/cm., and σ is the surface tension of solution, dynes/cm.

Metcalfe (12) has studied the effects of physical properties of the liquid and gas, column diameter, packed height, and size of packing on the flooding velocities. One inch, three-fourths inch, one-half inch, and one-fourth inch Berl saddles, five-eighths inch glass spheres, and one-half inch Intalox saddles were used for packing. Packed heights were varied from one foot to sixteen feet. Columns of three different diameters were used ranging from two inches to eight inches. Air and carbon dioxide were used for the gas and capella oil, carbon tetrachloride, ethanol, kerosene, methyl ethyl ketone, toluene, and water were used as the liquid. It was observed that great care was necessary in the packing procedure for Berl saddles. Metcalfe found that a change in packed height may alter the flooding velocity by as much as seventy per cent. Also, for any column there is a minimum packed height above which no further effect of height is noticeable.

McManus (13) studied the effects of packing size, column diameter, and packed heights in columns packed with Raschig rings. Flooding data were obtained for columns two, four, and eight inches in diameter packed with various heights of one-fourth, one-half, three-fourths, and one inch Raschig rings using a system of air and water. The flooding data showed little deviation from the curve of Lobo et al. (8) on a Sherwood type correlation.

Dell and Pratt (14) have derived a theoretical equation which represents a correlation of available flooding data for packed distillation and absorption columns. They state that their equation is not applicable to one-fourth inch or smaller size packing.

Little or no work has been performed utilizing laboratory size packing in small diameter columns. The purpose of this investigation was to obtain data for columns of one, one and one-half, and two inches in diameter packed with one-fourth inch Berl saddles, one-fourth inch single turn glass helices, and 0.16 inch by 0.16 inch Cannon protruded metal packing to a height of approximately three and one-half feet. Data were also obtained for one-eighth inch diameter eight turn glass helices in a column one and one-half inches in diameter and for one-fourth inch diameter Catalin spheres in columns of one, and one and one-half inches in diameter packed to a height of approximately three and one-half feet.

CHAPTER II

EQUIPMENT AND MATERIALS

The columns used in this investigation were pyrex glass pipe, manufactured in four foot lengths by the Corning Glass Works. One, one and one-half, and two inch internal diameter columns were used. The glass columns were connected to the base by use of adapter flanges. A pressure tap was located just below the pipe flange as shown in Figure 1. This tap was connected to one leg of a water manometer, the other leg being open to the atmosphere. The pressure drop across the packed column was measured by this manometer. The liquid exit from the base was through a vertical U-tube which served to maintain a liquid seal on the bottom of the column. The gas inlet was installed below the flange and concentric with the liquid exit. The columns were positioned vertically by means of a turnbuckle arrangement to the supporting superstructure.

The liquid was supplied from a fifty-five gallon drum fitted with a constant overflow. Suction was taken from the drum by a Pacific Pump Company Model 105 centrifugal pump which discharged to either of two Fischer & Porter rotameters. The rotameters had ranges of 0.01 to 0.7 pounds per minute and 0.4 to 5.2 pounds per minute, respectively. The liquid was led from the rotameters to a distributer head located at the top of the column. Three different distributer heads were used. For the two inch column, a one-half inch pipe cap with six holes, three-thirty seconds inch in diameter, drilled in a concentric circular pattern was

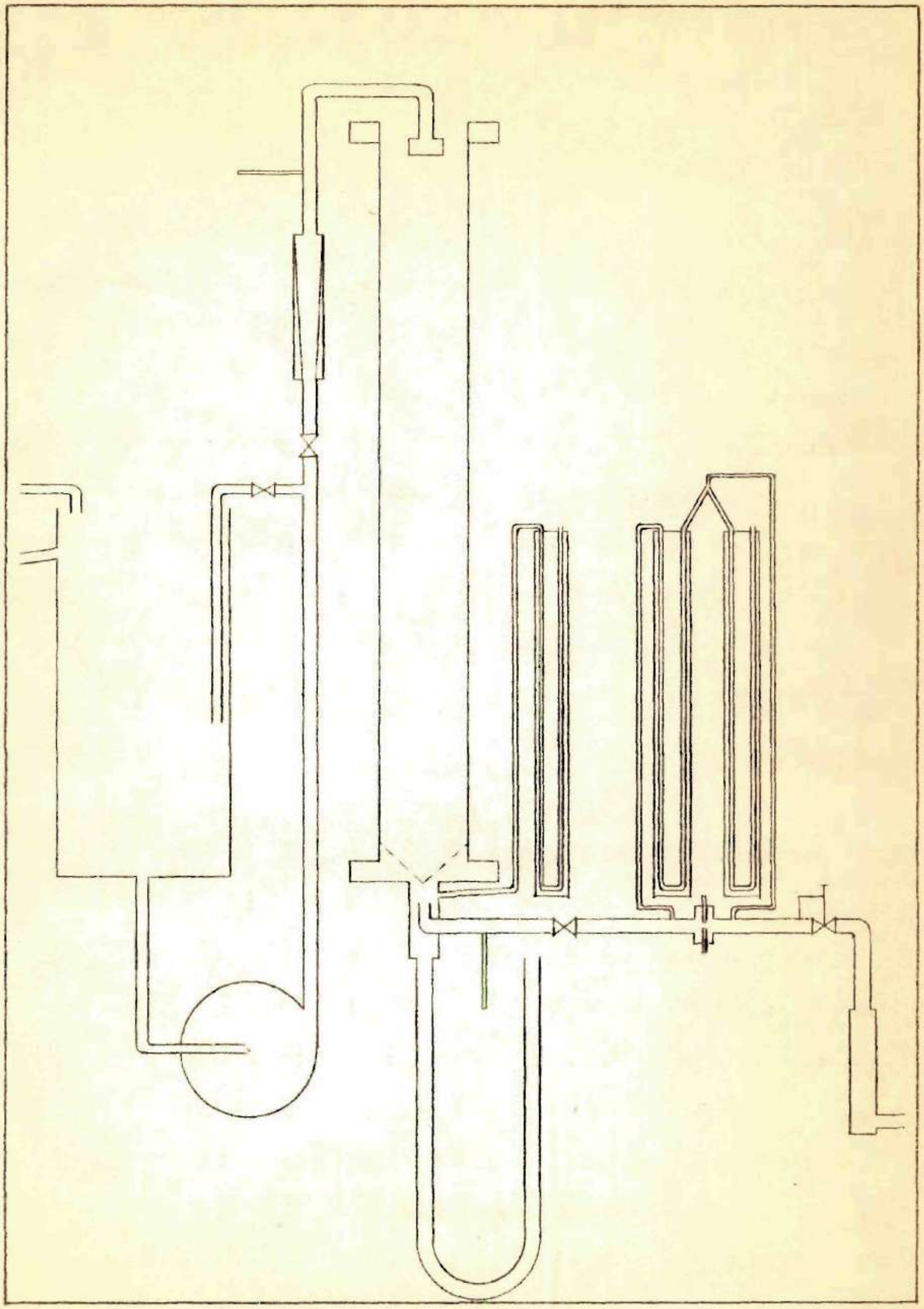

Figure 1. Diagram of Equipment

used. For the one and one-half inch column, a one-fourth inch pipe cap with eight holes one-sixteenth inch in diameter was used. For the one inch column, a one-fourth inch pipe cap with four holes one-sixteenth inch in diameter was used.

Air was supplied at 90 to 120 psig by a compressor. The pressure was reduced to 25 psig by a pressure reducing valve. The air then passed through a filter element which was charged with glass wool to remove any moisture or dust which may be present in the air. From the filter the air passed through another pressure reducing valve that was easily adjusted to maintain a constant pressure upstream from the metering orifice at all gas flow rates. The pressure drop across the calibrated orifice was measured by use of a water filled manometer. The pressure upstream of the orifice was measured by a mercury filled manometer. The flow of air to the column was regulated through a one-fourth inch needle valve.

Throughout this investigation the liquid used was water and the gas used was air.

The packing material, with the exception of Berl saddles, was supported on an inverted conical wire screen which was fabricated from wire screen of one-eighth inch mesh. The Berl saddles were supported on a layer of one-half inch Berl saddles on a flat wire screen of one-half inch mesh. Physical properties of the packing materials used are presented in Table 1. One-fourth inch Berl saddles, one-fourth inch single turn glass helices, 0.16 inch by 0.16 inch Cannon protruded metal packing, one-eighth inch diameter eight turn glass helices, and one-fourth inch Catalin spheres were used as packing material.

CHAPTER III

PROCEDURE

The procedures used in packing the columns were varied for different types of packings. In the case of Berl saddles, the column was filled with water and the packing pieces were dropped in one at a time. The procedure described by Cannon (15) was used in the case of the Cannon protruded metal packing. The packing was dropped into the column through a funnel located at least three feet above the bed of packing. Cannon did not state whether the column was filled with liquid or dry. Tests showed that when this packing was dropped into a water filled column, the packing formed in large groups on the surface of the water and fell to the bed as a mass. It was decided to charge the packing to a dry column. The single turn glass helices, eight turn glass helices, and the Catalin spheres were packed with the same procedure as that used for the protruded metal packing. In no case did flooding occur at the packing support.

The fraction of free volume of the packed bed could be determined by two methods noted in the literature. One method consists of measuring the quantity of water drained off of a previously filled packed section and is referred to as "drained wet voids". The method of "dry voids" was chosen for this work. The porosity of the bed was determined by completely drying the bed by flowing air through it for a number of hours. Water was then forced into the bottom of the column to a point just above the bottom layer of packing. Water was added from the top of the column until the level was just below the top layer of packing, and the quantity recorded as the fractional void space. The volume of the empty column was determined by the above procedure and the porosity of the bed was calculated. Tests showed that the values of F determined by "drained wet voids" were as much as six per cent lower than those determined by "dry voids" for the same bed.

The average volumes of the various types of packing studied were determined by volumetric displacement in water of one hundred Berl saddles, five hundred eight turn glass helices, four hundred single turn glass helices, and one thousand protruded metal packing pieces. The average volume of one sphere was calculated from the average diameter. The number of packing pieces in any packed section was calculated from this volume and the porosity. The surface area reported by the manufacturer for one Berl saddle was used in this work. Average surface areas for one piece of the remaining types of packing were determined by actual physical measurements of several units of each type. The values of S were calculated from these surface areas and the number of packing pieces per unit volume of column.

To determine the flooding velocities, a liquid flow rate was fixed at an arbitrary value for each determination. The initial gas flow rate was chosen low enough so that it would be well below the flooding velocity. The gas flow rate was then increased in small increments until the flooding velocity was reached. The time lapse between the increases of gas flow rate was governed by the time required to reach steady state. It was assumed that steady state conditions existed when the pressure drop across the packed column remained constant for the set flow rates for approximately five minutes. The pressure drop across the packed column, the water temperature, the air temperature, the pressure drop across the gas measuring orifice, the upstream pressure, and the liquid flow rate were recorded at each steady state condition during a run. As will be pointed out later, the recording of the pressure drop across the packed column was discontinued after a number of tests and thereafter used only as a means of checking. In each case where this pressure was recorded, data were obtained from which a plot of the logarithm of the pressure drop across the packed column versus the logarithm of the gas mass flow rate was made. The pressure drop versus gas rate curves were characteristic of those reported by White (1). The flood points thus determined by the graphical method of White were very close to the visual flood points determined in this work. It was decided to obtain the flood points by the visual method for this investigation and the pressure drop across the packed column was used merely as an occasional check.

All columns were packed to a height of approximately three and one-half feet with the exception of one series of runs made on Berl saddles in a two inch column packed to a height of twenty inches. In no case were the distribution points located more than three inches above the packing. This was shown by Metcalfe (12) to be desirable to obtain good liquid distribution.

CHAPTER IV

DISCUSSION OF RESULTS

All original data obtained in this investigation are presented in Figure 2 on a Sherwood _et al_. type plot. For all packed columns studied, the mass velocity of the gas required for flooding the column, at a fixed liquid rate, decreased with decreasing column diameter for each type of packing material as was expected. The generalized curve of Sherwood _et al_. will subsequently be referred to as the reference curve.

Columns Packed with Berl Saddles.--The data for columns packed to a height of approximately 3.5 feet with one-fourth inch Berl saddles are shown in Figure 3. The curve for a two inch diameter column has a maximum deviation from the reference curve of twenty five per cent, for a one and one-half inch column the deviation is fifty three per cent, and for a one inch column the deviation is thirty eight per cent. The relative magnitude and direction of deviation from the reference curve is that expected as shown by Metcalfe (12) where he found that for a given size of packing, the flooding rates are higher in large diameter than in small diameter columns. Another factor which may affect flooding rates is the ratio of column diameter to packing size. It has been shown by some investigators (3, 12, and 13) that when this ratio is greater than eight to one there is no noticeable effect on flooding velocities. However, when this ratio is less than eight to one there is a tendency for flooding velocities to

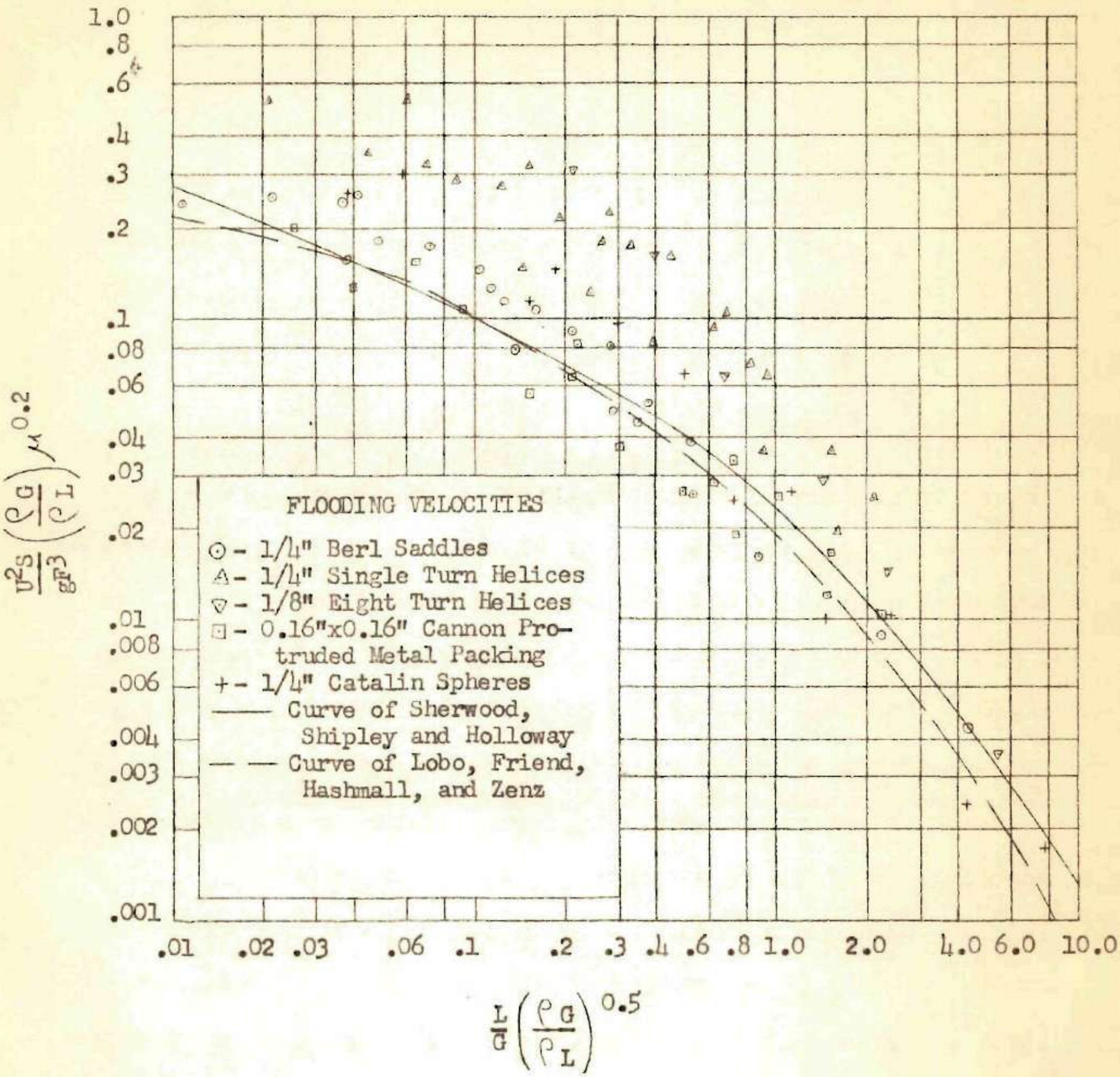

Figure 2. Summary of Data. Sherwood Correlation

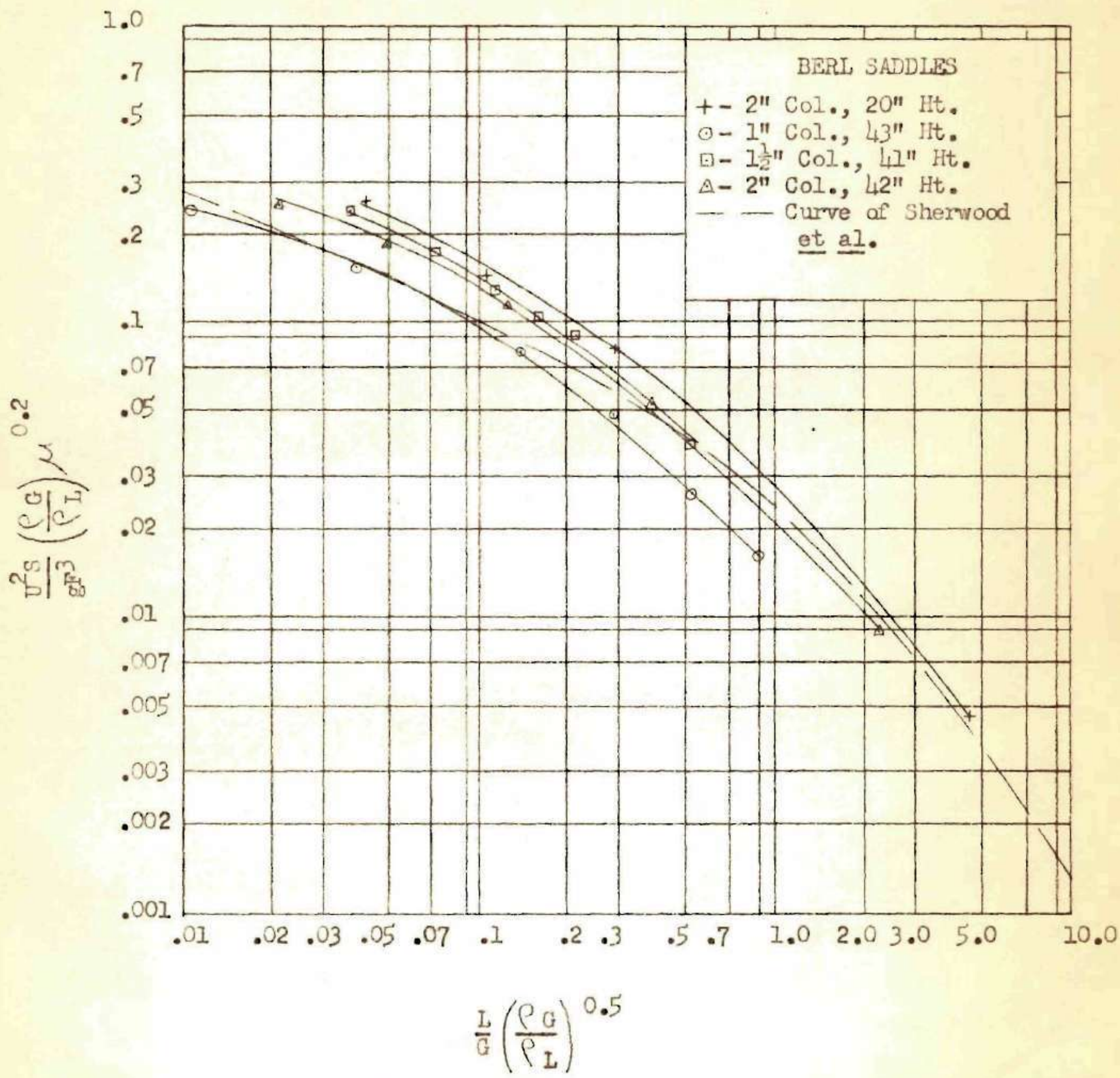

Figure 3. Effect of Column Diameter on Flooding Velocities

become higher. This may explain why the curve for the one and one-half inch column is slightly above that for the two inch column, although judging from the effect of column diameter alone, the curve for the one and one-half inch column should lie below that for the two inch column.

A curve representing data for a two inch diameter column packed to a height of twenty inches is also shown in Figure 3. This curve lies a maximum of twenty seven per cent higher than the curve for the two inch column with approximately 3.5 feet packed height, indicating an effect of packed height on flooding velocities. Metcalfe (12) has shown that variation in packed height may affect flooding velocities by as much as seventy per cent.

Columns Packed with Cannon Protruded Metal Packing.--Figure 4 illustrates the effect of column diameter on flooding velocities in small diameter columns packed to a height of approximately 3.5 feet with 0.16 inch by 0.16 inch Cannon protruded metal packing. The curve representing data for a two inch diameter column has a maximum deviation from the reference curve of twenty two per cent, and a one and one-half inch column has a maximum deviation of twenty five per cent. The curve for a one inch diameter column has a deviation from the reference curve of thirty six per cent. Again, the relative magnitude and direction of deviation from the reference curve is that expected. There is a negligible effect of column diameter to packing size ratio since the packing is so small and the effect of column diameter controls.

Columns Packed with Single Turn Helices.--The flooding velocity curves for one-fourth inch single turn glass helices for all columns investigated lie

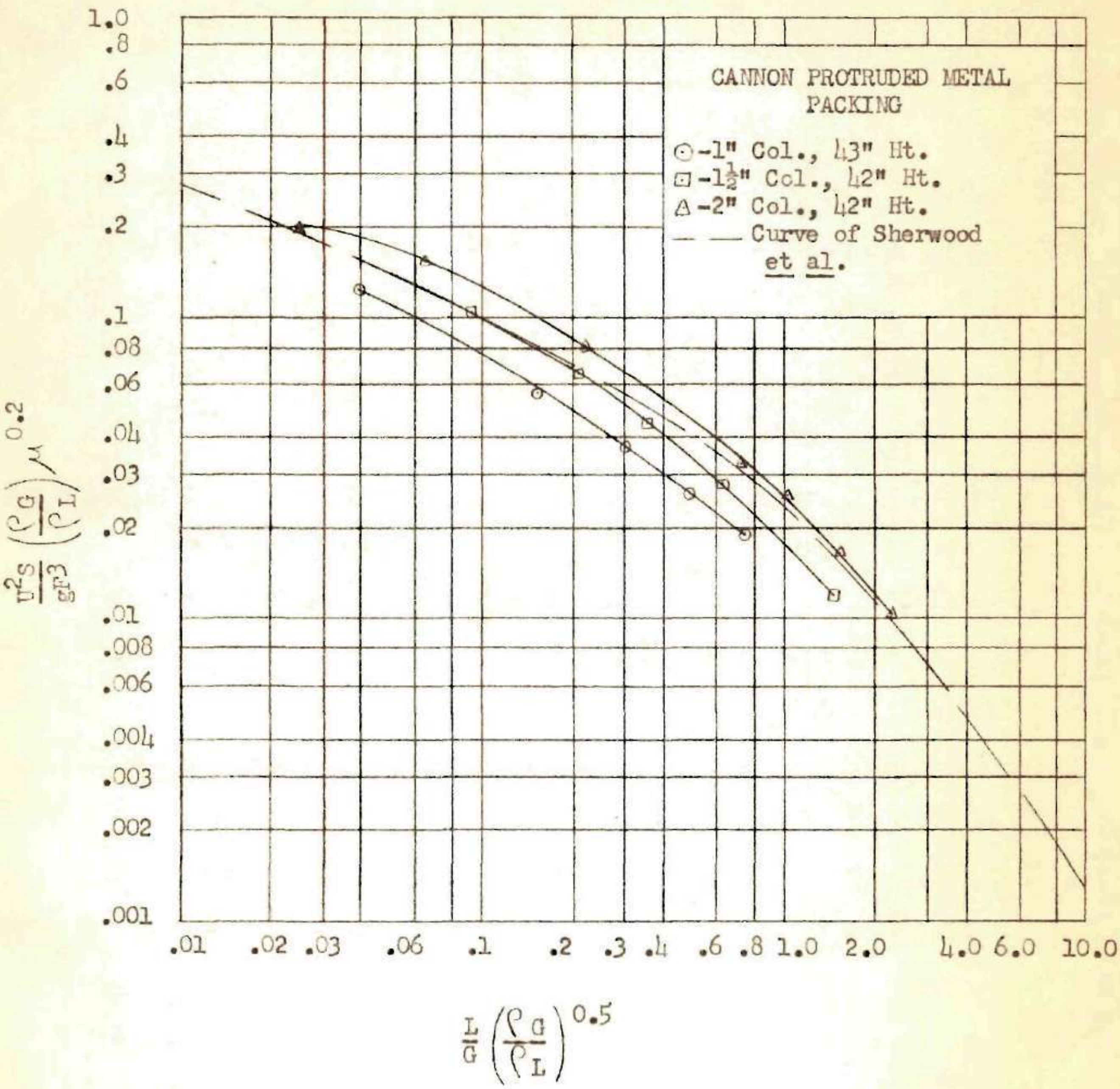

Figure 4. Effect of Column Diameter on Flooding Velocities

considerably above the reference curve (see Figure 5). The curve for a two inch diameter column with a packed height of approximately 3.5 feet has a maximum deviation from the reference curve of ninety one per cent.

Two curves are shown for a one and one-half inch diameter column. The agreement between the two curves does not indicate good reproducability. This investigator believes that since the glass helices were fragile and consequently considerable breakage occurred during the operations of packing and unpacking, the curves represent data for what amounts to different types of packing. There was a variation of seventeen per cent between the calculated fractional voids of the two columns indicating different packing characteristics. It was necessary to re-use the same packing throughout this work. It is recommended that a more durable packing material be used in future investigations of flooding velocities involving single turn helices. One of the two curves has a maximum deviation of three hundred per cent while the other curve has a maximum deviation of one hundred thirty five per cent above the reference curve.

The curve for the data of a one inch diameter column has a uniform deviation of approximately one hundred fifty per cent above the reference curve.

It was noticed during the experimental work on helices that there was considerable channeling of the liquid near the column wall which would be expected to cause the flooding velocities to be higher than in beds where channeling does not exist. The effect of channeling, as shown by a number of investigators, is to make a column more difficult to flood. The lack of a trend in the curves for single turn helices with respect

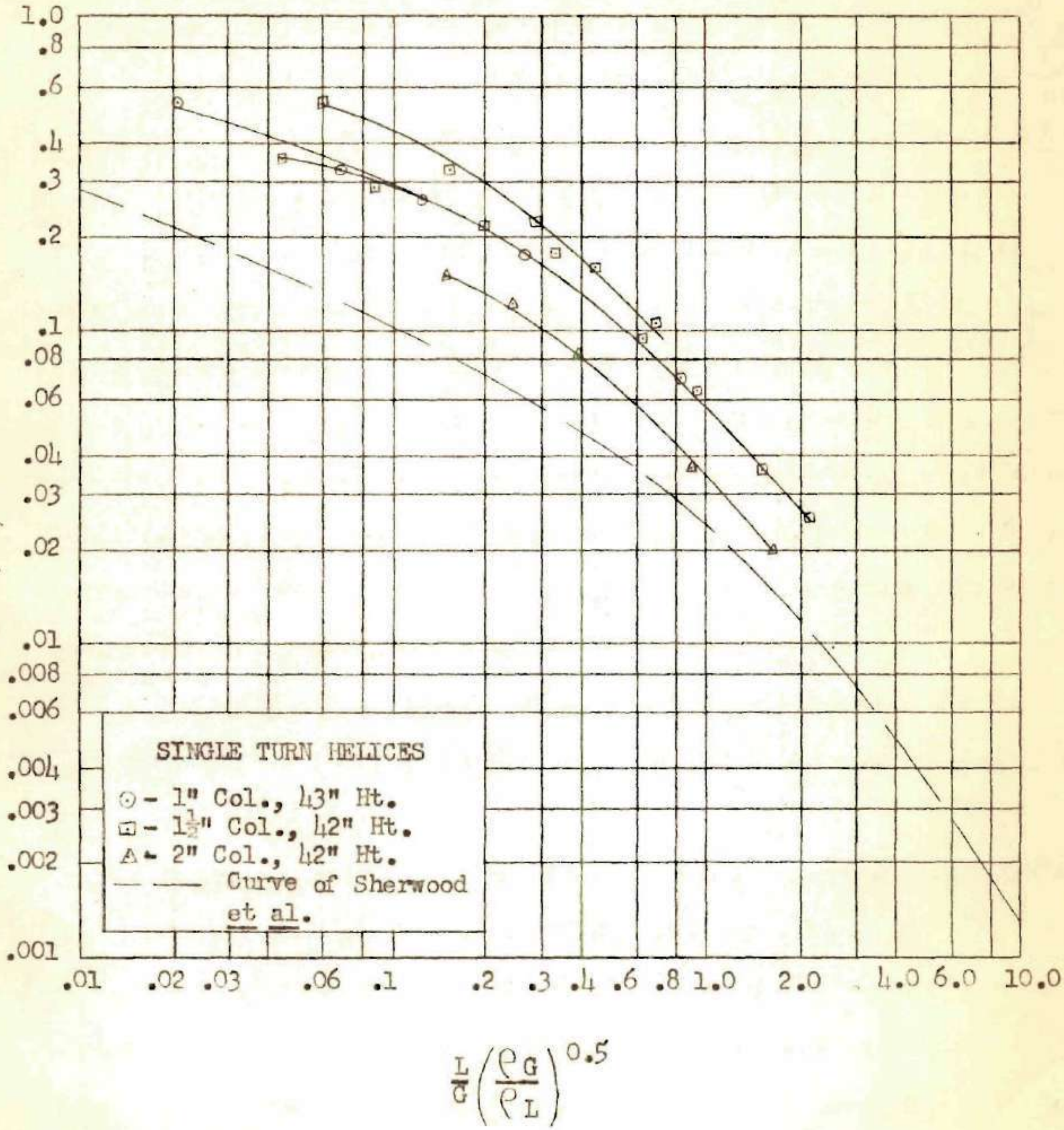

Figure 5. Effect of Column Diameter on Flooding Velocities

to diameter as a parameter may be explained by the fact that the characteristics of the packing material changed considerably between runs.

Columns Packed with Catalin Spheres.--Additional flooding data were obtained for one-fourth inch Catalin spheres in columns one, and one and one-half inches in diameter packed to a height of approximately 3.5 feet. The resulting flooding velocity curves are shown in Figure 6. The curve for a one and one-half inch diameter column has a maximum deviation from the reference curve of one hundred twenty seven per cent. The curve for a one inch column is approximately forty per cent below that for a one and one-half inch column. With increasing liquid rates, there is a rapid decrease of the gas velocity required for flooding this type of packing in small diameter columns.

Columns Packed with Eight Turn Helices.--One series of runs made in a one and one-half inch diameter column, packed to a height of approximately 3.5 feet with one-eighth inch diameter eight turn glass helices was violently flooded during the first run at a low liquid flow rate. This caused subsequent floodings to occur at the top of the packed section at relatively low gas flow rates.

Metcalfe (12) has found that after a column has been flooded violently the packing will be rearranged at some point in the column and subsequent floodings will occur at this point at reduced gas rates for a given liquid rate. This investigator believes that the flooding velocity characteristics of one-eighth inch eight turn glass helices are much the same as for one-fourth inch single turn glass helices. The data for the above

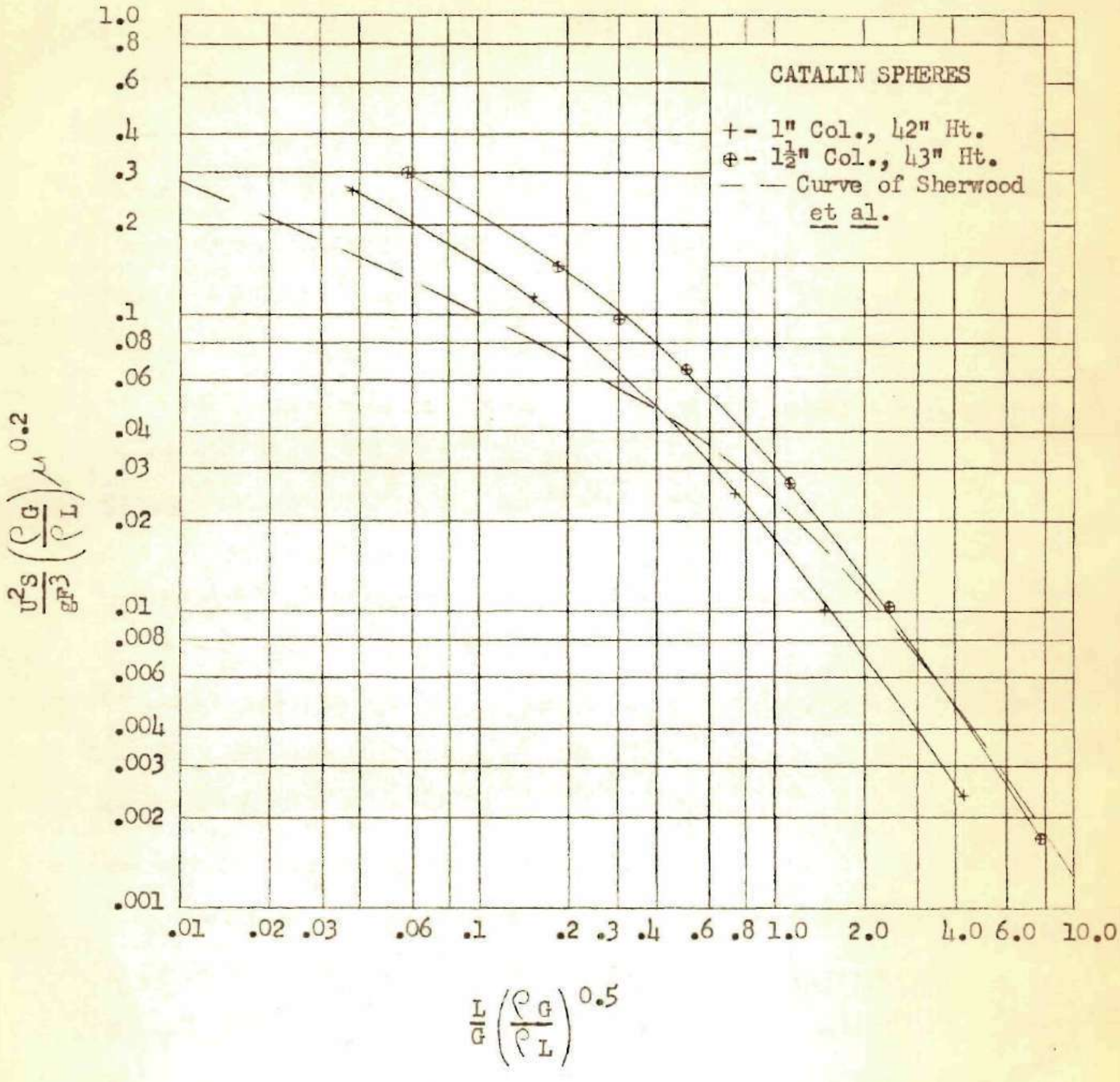

Figure 6. Effect of Column Diameter
on Flooding Velocities

series of runs are presented in Figure 2. It is recommended that more data be obtained for this type packing material in future investigations. This type of packing material was investigated as a matter of interest only and it was due to a lack of time that more data was not obtained for it.

CHAPTER V

CONCLUSIONS

From the results obtained in this investigation the following conclusions may be drawn:

1. The flooding velocity data for small diameter columns packed with one-fourth inch Berl saddles follow the generalized correlation curve of Sherwood, Shipley, and Holloway (2) within approximately fifty per cent. It is generally considered that this agreement is sufficiently good for most engineering design calculations.

2. The flooding velocity data for small diameter columns packed with 0.16 inch by 0.16 inch Cannon protruded metal packing follow the generalized correlation curve of Sherwood, Shipley, and Holloway (2) within thirty five per cent. This is considered to be reasonably good agreement for application to most engineering design calculations.

3. The flooding velocity data for small diameter columns packed with one-fourth inch single turn glass helices are not in agreement with the generalized correlation curve of Sherwood, Shipley, and Holloway (2) and may deviate by as much as three hundred per cent.

4. The flooding velocity data for small diameter columns packed with one-fourth inch Catalin spheres are not in agreement with the generalized correlation curve of Sherwood, Shipley, and Holloway (2) and may deviate by as much as one hundred thirty per cent.

5. Column diameter has an effect on flooding velocities for a given packing size and a given packed height such that flooding velocities decrease with decreasing column diameter.

BIBLIOGRAPHY

1. White, A. M., Trans. Am. Inst. Chem. Engrs., 31, 390 (1935).

2. Sherwood, T. K., G. H. Shipley, and F. A. L. Holloway, Ind. Eng. Chem., 30, 765 (1938).

3. Baker, T. C., T. H. Chilton, and H. C. Vernon, Trans. Am. Inst. Chem. Engrs., 31, 296 (1935).

4. Elgin, J. C., and F. B. Weiss, Ind. Eng. Chem., 31, 435 (1939).

5. Sarchet, B. R., Trans. Am. Inst. Chem. Engrs., 38, 283 (1942).

6. Schoenborn, E. M., and W. C. Dougherty, Trans. Am. Inst. Chem. Engrs., 40, 51 (1944).

7. Bain, W. A., Jr., and O. A. Hougen, Trans. Am. Inst. Chem. Engrs., 40, 29 (1944).

8. Lobo, W. E., L. Friend, F. Hashmall, and F. A. Zenz, Trans. Am. Inst. Chem. Engrs., 41, 693 (1945).

9. Zenz, F. A., Chem. Eng. Prog., 43, 415 (1947).

10. Lerner, B. J., and C. S. Grove, Jr., Ind. Eng. Chem., 43, 216 (1951).

11. Newton, W. M., J. W. Mason, T. B. Metcalfe, and C. O. Summers, Pet. Ref., 31, No. 10, 141 (1952).

12. Metcalfe, T. B., A Study of Flooding in Packed Columns, Ph.D. Thesis in Chemical Engineering, Georgia Institute of Technology, 1952.

13. McManus, J. J., Jr., M.S. Thesis in Chemical Engineering, Georgia Institute of Technology, 1952.

14. Dell, F. R., and H. R. C. Pratt, J. Appl. Chem., 2, 429 (1952).

15. Cannon, M. R., Ind. Eng. Chem., 41, 1953 (1949).

APPENDIX

Table 1. Physical Dimensions of One Packing Piece

Packing	Size	Surface Area, $Ft.^2$	Volume, $Ft.^3$
Berl Saddle	1/4 inch	0.002425*	0.00000410
Single Turn Glass Helix	1/4 inch	0.000365	0.0000001731
Protruded Metal	0.16 inch x 0.16 inch	0.0006375	0.0000000705
Eight Turn Glass Helix	1/8 inch x 3/8 inch	0.001808	0.000000825
Catalin Sphere	1/4 inch	0.001462	0.00000526

*Manufacturer.

Table 2. Flooding Velocities

Condition of Packing	Air Temp., °F.	Gas Flow Rate Ft.^{3}/min.	Water Temp., °F.	Liquid Flow Rate #/min.	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}$	$\frac{V^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
1/4" Saddles	78	3.79	80	0.173	0.02135	0.251
2" Column	78	3.22	80	0.335	0.0487	0.1818
42" Height	78	2.56	80	0.685	0.1252	0.1148
F = 0.635	78	1.73	80	1.395	0.377	0.0525
S = 216.5	78	0.715	80	3.55	2.215	0.00896
1/4" Saddles	82	2.18	82	0.173	0.0372	0.243
$1\frac{1}{2}$" Column	82	1.85	82	0.28	0.0709	0.1745
41" Height	82	1.59	82	0.387	0.114	0.1291
F = 0.646	80	1.45	82	0.496	0.16	0.1071
S = 209.5	79	1.33	82	0.6	0.211	0.0902
	79	0.87	82	0.97	0.522	0.0386
1/4" Saddles	79	1.02	80	0.024	0.01098	0.2425
1" Column	79	0.811	80	0.067	0.0385	0.1535
43" Height	79	0.582	80	0.173	0.1385	0.079
F = 0.660	79	0.46	80	0.28	0.284	0.0495
S = 201.0	79	0.338	80	0.387	0.534	0.0266
	79	0.263	80	0.496	0.88	0.01611

(Continued)

Table 2. Flooding Velocities (Continued)

Condition of Packing	Air Temp., °F.	Gas Flow Rate Ft.^{3}/min.	Water Temp., °F.	Liquid Flow Rate #/min.	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}$	$\frac{V^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
Protruded Metal	80	3.23	82	0.173	0.0251	0.20
2" Column	80	2.82	85	0.395	0.0656	0.152
42" Height	80	2.065	85	0.98	0.222	0.0818
F = 0.910	85	1.325	84	2.02	0.714	0.03375
S = 699.0	85	1.16	84	2.52	1.018	0.02585
	85	0.93	84	3.03	1.525	0.01659
	85	0.73	84	3.54	2.27	0.01024
Protruded Metal	79	1.4	78	0.28	0.0932	0.1078
1½" Column	78	1.086	80	0.49	0.2105	0.0649
42" Height	78	0.907	80	0.685	0.352	0.0451
F = 0.927	78	0.721	80	0.97	0.628	0.02855
S = 663.0	78	0.467	80	1.495	1.49	0.012
Protruded Metal	78	0.8	80	0.067	0.0391	0.126
1" Column	78	0.535	80	0.173	0.151	0.0562
43" Height	76	0.435	80	0.28	0.301	0.0372
F = 0.946	78	0.368	80	0.387	0.491	0.0266
S = 496.5	78	0.312	80	0.496	0.743	0.01917

(Continued)

Table 2. Flooding Velocities (Continued)

Condition of Packing	Air Temp., °F.	Gas Flow Rate Ft.^{3}/min.	Water Temp., °F.	Liquid Flow Rate #/min.	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}$	$\frac{V^2 S}{g F^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
1/4" Single Turn	88	3.175	86	0.98	0.148	0.1495
Glass Helices	85	2.86	85	1.495	0.242	0.121
2" Column	85	2.39	85	2.02	0.392	0.0844
42" Height	85	1.565	85	3.03	0.90	0.0362
F = 0.818	85	1.16	85	4.06	1.622	0.0199
S = 384.0						
1/4" Single Turn	80	3.81	78	0.49	0.0602	0.532
Glass Helices	85	2.98	83	0.97	0.152	0.326
1½" Column	85	2.47	83	1.495	0.283	0.2245
42" Height	85	2.09	83	2.02	0.452	0.160
F = 0.842	85	1.695	83	2.52	0.694	0.1055
S = 331.0						
1/4" Single Turn	80	1.5	82	0.067	0.0209	0.537
Glass Helices	80	1.17	82	0.173	0.0691	0.327
1" Column	80	1.065	82	0.28	0.123	0.272
43" Height	80	0.87	82	0.496	0.267	0.180
F = 0.815	80	0.545	82	0.97	0.834	0.0709
S = 392.0						

(Continued)

Table 2. Flooding Velocities (Continued)

Condition of Packing	Air Temp., °F.	Gas Flow Rate Ft.^{3}/min.	Water Temp., °F.	Liquid Flow Rate #/min.	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}$	$\frac{V^2 S}{g F^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
1/4" Spheres	82	1.37	85	0.173	0.059	0.303
1½" Column	82	0.957	85	0.387	0.189	0.1475
43" Height	82	0.772	85	0.496	0.30	0.0962
F = 0.406	82	0.64	84	0.685	0.50	0.066
S = 165.3	80	0.406	84	0.97	1.115	0.02665
	80	0.252	84	1.29	2.39	0.01028
	79	0.103	84	1.695	7.68	0.001715
1/4" Spheres	78	0.784	80	0.067	0.0393	0.26
1" Column	79	0.517	80	0.173	0.154	0.1132
42" Height	79	0.241	81	0.387	0.739	0.0245
F = 0.483	80	0.155	82	0.496	1.471	0.01014
S = 143.6	81	0.075	82	0.71	4.36	0.002375
1/4" Saddles	79	3.80	67	0.335	0.0413	0.26
2" Column	81	2.87	76	0.65	0.106	0.1461
20" Height	81	2.13	75	1.30	0.286	0.08075
F = 0.635	78	0.483	65	4.40	4.26	0.00436
S = 216.5						

(Continued)

Table 2. Flooding Velocities (Continued)

Condition of Packing	Air Temp., °F.	Gas Flow Rate $Ft.^3/min.$	Water Temp., °F.	Liquid Flow Rate #/min.	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}$	$\frac{V^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
1/4" Single Turn	89	2.915	87	0.28	0.0448	0.352
Glass Helices	86	2.63	84	0.496	0.088	0.2865
$1\frac{1}{2}$" Column	87	2.30	85	0.97	0.1977	0.2195
42" Height	89	2.06	86	1.495	0.339	0.1757
F = 0.828	88	1.51	87	2.02	0.625	0.0943
S = 363.0	88	1.249	87	2.52	0.943	0.0646
	88	0.94	87	3.03	1.508	0.0366
	88	0.78	87	3.54	2.12	0.0252
1/8" Eight Turn	86	3.30	86	1.495	0.2115	0.317
Glass Helices	86	2.375	86	2.02	0.397	0.1642
$1\frac{1}{2}$" Column	86	1.49	86	2.52	0.789	0.0645
41" Height	86	1.01	86	3.03	1.402	0.02965
F = 0.865	86	0.705	86	3.54	2.35	0.01443
S = 291.0	86	0.35	86	4.06	5.42	0.00357